Invisible Z' as a probe of extra dimensions at the CERN LHC

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A class of extra dimensional models with a warped metric predict tunneling of a massive particle localized on our brane and escaping into additional dimensions. The experimental signature of this effect is the disappearance of the particle from our world, i.e. the *particle → invisible* decay. We point out that measurements of $Z' \to invisible$ decay width of a new heavy gauge boson Z' at the CERN LHC can be effectively used to probe the existence of large extra dimensions. This result enhances motivations for a more sensitive search and study for this decay mode and suggests additional direction for testing extra dimensions in collider experiments.

Presently there is a big interest in models with additional dimensions [1]-[4] which might provide solution to the gauge hierarchy problem [5]-[8], for a review see e.g. [9]. For instance, as it has been shown in the five dimensional model, so called RS 2-model [6], there exists a thin-brane solution to the 5-dimensional Einstein equations which has flat 4-dimensional hypersurfaces,

$$ds^2 = a^2(z)\eta_{\mu\nu}dx^\mu dx^\nu - dz^2. \tag{1}$$

Here

$$a(z) = exp(-k|z|) \tag{2}$$

and the parameter $k > 0$ is determined by the 5-dimensional Planck mass and bulk cosmological constant and represents a scale of new physics.

Not long ago, a peculiar feature of massive matter in brane world has been reported [10]. It has been shown that particles initially located on our brane may leave the brane and disappear into extra dimensions. These kind of transitions have been found to be generic in a class of models of localization of particles on a brane. The localization becomes incomplete if particles get masses and they could tunnel from the brane into extra dimensions. The experimental signature of this effect is the disappearance of a particle in our world, i.e. the *particle → invisible* decay.

Particles disappearing into bulk are inherent also in string theory, e.g. the disappearance into bulk have been found in the context of noncommutative gauge theories [11]. The difference, though, is that massless gauge bosons (photon and gluon) as well as particles charged under unbroken gauge group are strictly bound to the brane, and only massive and electrically neutral gauge bosons can disappear into bulk. Interestingly, this process in the noncommutative soliton context is opened up by the Higgs mechanism [11]. For disappearance processes to be reasonably fast, the string energy scale should be in 1-10 TeV range. Such low string scale is behind many ideas beyond the SM, see, e.g., Ref. [11] and references therein.

The case of the electromagnetic field propagating in the Randall-Sundram type of metric in the presence of extra compact dimensions [12, 13] has been considered in [13], where it was shown that the transition rate of a virtual photon into additional dimensions is different from zero. This effect could result in disappearance of a neutral system, orthopositronium $(o - Ps)$ [14], a triplet bound state of an electron and positron, at a rate within two orders of magnitude of the present best experimental limit on the branching ratio of the $o - Ps \to invisible$ decay $Br(o - Ps \to inv) < 4.3 \times 10^{-7}$ (90% C.L.) from the recent ETH-INR experiment [15].

The lower limit on the $k-$parameter, which can be extracted from the results of this experiment is

$$k \gtrsim 0.5 TeV \tag{3}$$

Stronger bounds on the parameter k for photons escaping into extra dimensions can be obtained from astrophysical considerations [16].

Consider now the disappearance of the Z bosons. The transition rate into additional dimension(s) of the Z on-shell is given by [13, 14]

$$\Gamma = q(n)M_Z\left(\frac{M_Z}{k}\right)^n \tag{4}$$

where $q(n)$ is a numerical coefficient, and M_Z is the Z mass. To make a quantitative estimate, we take $n = 2$ ((4+2+1)-dimensional space-time). In this case the Z disappearance rate is given by [14]

$$\Gamma = \frac{\pi M_Z}{16}\left(\frac{M_Z}{k}\right)^2 \tag{5}$$

Important bounds on the parameter k and $\Gamma(Z \to add. dim.)$ arise from the combined LEP result on the precise measurements of the total and partial Z widths [14, 17]:

$$k \gtrsim 17 \, TeV \tag{6}$$

The limit of Eq.(6) is much stronger than the one of Eq.(3) obtained from positronium measurements. Note that combined result on direct LEP measurements of the invisible width [18] gives less stringent limit [14]:
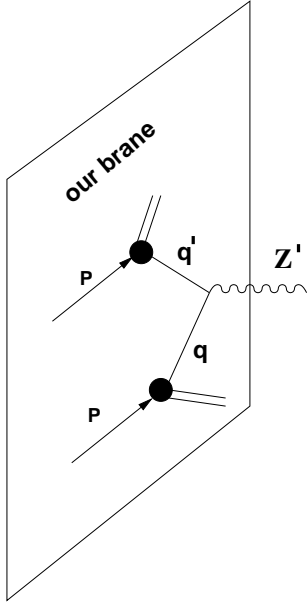
$$k \gtrsim 4 \, TeV \tag{7}$$

FIG. 1: Schematic illustration of the production and disappearance processes of Z' bosons in pp collisions at LHC: protons and quarks propagate along the our brane while Z' escapes into extra dimensions.

To solve the gauge hierarchy problem models with additional dimension(s) one may expect

$$k \simeq 10\ TeV \qquad (8)$$

which is consistent with bounds of Eqs.(3,6,7).

Similarly, consider now the new TeV-scale boson Z', which appears in many models of physics beyond the SM, for a review see e.g. [19]. Z' bosons that decay to leptons have a simple, clean experimental signature, and consequently can be searched for up to high masses at colliders. Current direct search limits from Tevatron experiments restrict the Z' mass to be greater than about 900 GeV when its couplings to SM fermions are identical to those of the Z boson [17].

The Z' is a good candidate for the searching for effect of disappearance into additional dimension(s), since it potentially could be discovered at the LHC with a mass up to 5 TeV, see e.g. [20]. Schematically, the disappearance of Z' produced in pp collisions into extra dimensions is illustrated in Fig. 1. As it follows from Eqs.(5,8), for $M_Z \lesssim 5$ TeV one may expect

$$\Gamma(Z' \to add\ dim) \lesssim 10\ GeV \qquad (9)$$

Consider, for comparison the $Z' \to \nu\nu$ decay rate to the SM neutrinos in several canonical Z' models [19]. First we shortly describe these models and the SM fermions couplings the Z'.

- the E$_6$ models - are described by the breaking chain
$E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi \to$

$SM \times U(1)_\beta$. Many studies of Z' are focusing on the two extra $U(1)'$ which occur in the above decomposition of the E_6. The lightest Z' is defined as :

$$Z' = Z'_\chi cos\beta + Z'_\psi sin\beta \qquad (10)$$

where the values $\beta = 0$ and $\beta = \pi/2$ corresponds to pure Z'_χ and Z'_ψ states of the χ- and ψ-model, respectively. The value $\beta = arctan(-\sqrt{5/3})$ is related to a Z'_η boson that would originate from the direct breaking of E_6 to a rank-5 group in superstrings inspired models.

- the Left-Right Symmetric (LRSM) model is based on the symmetry group $SU_C(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U(1)_{B-L}$ [21], in which B and L are the baryon and lepton numbers, respectively. The model necessarily incorporates three additional gauge bosons $W_R^\pm$ and Z'. The most general Z' is coupled to a linear combination of right-handed and $B-L$ currents:

$$J_{LR}^\mu = \alpha_{LR} J_{3R}^\mu - (1/2\alpha_{LR}) J_{B-L}^\mu \qquad (11)$$

where $\alpha_{LR} = \sqrt{(c_W^2 g_R^2)/s_W^2 g_L^2) - 1}$, with $g_L = e/s_W$ and g_R are the $SU(2)_L$ and $SU(2)_R$ coupling constant with $s_W^2 = 1 - c_W^2 = sin^2\Theta_W$. The α_{LR}-parameter is restricted to be in the range $\sqrt{2/3} \lesssim \alpha_{LR} \lesssim \sqrt{2}$. The upper bound corresponds to the so-called manifest LRSM with $g_l = g_R$, while the lower bound corresponds to the χ-model discussed above, since $SO(10)$ can results to both $SU(5) \times U(1)$ and $SU(2)_R \otimes SU(2)_L \otimes U(1)$ breaking parameter.

- in the sequential model (SSM) the corresponding Z' boson has the same couplings to fermions as the Z of the SM. The Z' could be considered as an excited state of the ordinary Z in models with extra dimensions at the weak scale.

The Z' boson partial decay width into a fermion-antifermion pair is given by

$$\Gamma(Z' \to f\overline{f}) = N_C \frac{\alpha M_{Z'}}{6c_W^2} \sqrt{1-4\eta_f} \times$$
$$[(1+2\eta_f)(g_L^f)^2 + (1-4\eta_f)(g_R^f)^2] \qquad (12)$$

where N_C is a color factor ($N_C = 3$ for quarks and $N_C = 1$ for leptons), g_L^f, g_R^f are the left- and right-handed couplings of the Z' to the SM fermions, α is the electromagnetic coupling constant, which is $\alpha \simeq 1/128$ at the $M_{Z'}$ scale, and $\sqrt{\eta_f}(= m_f/m_{Z'})$ is assumed to be $\ll 1$. The left-handed couplings of the Z' to the SM neutrinos are $g_L^f = \frac{3cos\beta}{2\sqrt{6}} + \frac{\sqrt{10}sin\beta}{12}$ and $g_L^f = \frac{1}{2\alpha_{LR}}$ for E$_6$ and LRSM models, respectively, while the right-handed couplings $g_R^f = 0$ in both models. The $(g_L^f)^2$ is restricted to lie in the range $0.07(\beta \simeq \pi/2) \lesssim (g_L^f)^2 \lesssim 0.45\ (\beta \simeq 0.4)$

for the E$_6$ model[27] and in the range $1/8 \lesssim (g_L^f)^2 \lesssim 3/8$ for the LRSM model.

In Fig.2, the dependence of the rate $\Gamma(Z' \to add\ dim)$ and the total decay rate $\Gamma_i(Z' \to \nu_i\overline{\nu}_i)$ of Z' to the SM neutrinos are shown as a function of the Z' mass for different $k-$ parameters. The results are obtained for E$_6$ and LRSM models taking into account uncertainties in the g_L^f coupling. One can see, that for the most of
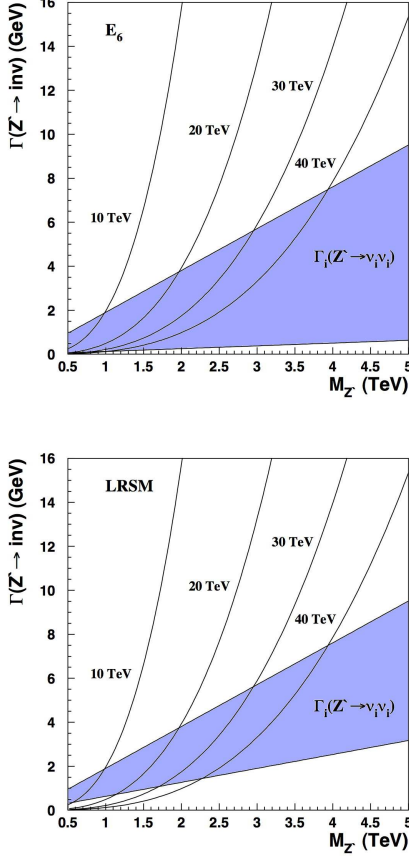

FIG. 2: The dependence of the rate $\Gamma(Z' \to add\ dim)$ as a function of the Z' mass for different $k-$parameters shown near the curves. The shaded region represents the possible values of $\Gamma_i(Z' \to \nu_i\overline{\nu}_i)$ decay rate calculated for E$_6$ (upper plot) and LRSM models taking into account uncertainties in the g_L^f coupling (see text).

the parameters space the $Z' \to add\ dim$ rate either is comparable or dominates the total $\Gamma_i(Z' \to \nu_i\overline{\nu}_i)$ rate. If, for example the Z' mass is $M_{Z'} = 1.5$ TeV and $k \simeq 10$ TeV, the $\Gamma(Z' \to add\ dim)$ rate is about factor 2 greater then the largest $\Gamma_i(Z' \to \nu_i\overline{\nu}_i)$ decay rate in the LRSM model. Hence, if Z' is observed at the LHC, the question of accurate measurements of its properties and, in particular of its invisible decay rate, is of great interest for possible observation of extra dimensions.

The experimental signature of $Z' \to inv$ process at the LHC is the large missing E_T ($\gtrsim 150 - 200$) GeV).

This signature is relatively clean, however, in order to discover process $Z' \to add\ dim$ one has to distinguish whether the extra invisible width $\Gamma(Z' \to add\ dim)$ could be determined over the background from the Z' decays into SM neutrinos.
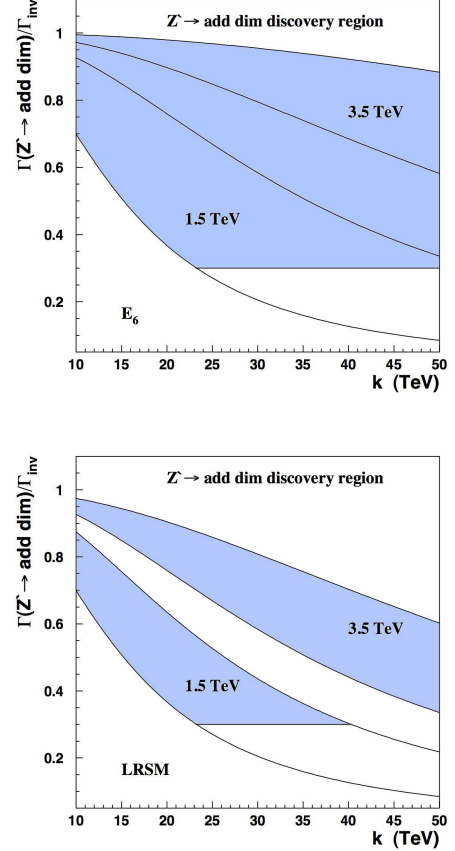

FIG. 3: Two regions of possible branching fraction $\Gamma(Z' \to add\ dim)/\Gamma_{inv}$ in E$_6$ (upper plot) and LRSM models determined for $M_{Z'} = 1.5$ and 3.5 TeV by taking into account uncertainties in the g_L^f coupling. The central part in the upper plot is the overlap between the regions, see plot below for comparison. The shaded areas corresponds to $\Gamma(Z' \to add\ dim)/\Gamma_{inv} \gtrsim 0.3$ for which the process $Z' \to add\ dim$ could be seen at the LHC for the integrated luminosity of 30 fb^{-1}.

Recently, an interesting analysis relevant to the present discussion has been reported [23, 24, 25]. It has been shown that among several reactions of Z' production in pp collisions at the LHC, the reaction $pp \to ZZ' \to l^+l^- + E_T^{miss}$ of associated Z and Z' production is quite convenient to study $Z' \to inv$ decay properties. It has been demonstrated that for the most popular models the invisible Z' decay can be seen over the SM background with a significance of $S/\sqrt{B} = 3$ at 10 fb^{-1}, while $S/\sqrt{B} = 5$ can be reached with 30 fb^{-1}.

An important observation is that if the only invisible decays of the Z' are to SM neutrinos, the invisible width

of this process can be predicted from the analysis of the Drell-Yan Z' production [24]. Then, the additional contribution $\Delta\Gamma_{inv}$ to the Γ_{inv} can be determined as an excess over expected $pp \to ZZ' \to l^+l^- + E_T^{miss}$ cross-section predicted by the analysis of on-peak data. The initial analysis demonstrates that if $\Delta\Gamma_{inv}$ contributes to the total invisible width at the level of $\gtrsim 30\%$, the corresponding underlying process can be discovered at the LHC for the integrated luminosity of 30 fb^{-1} [25].

In Fig.3, the regions of possible values for the decay branching fraction $R = \Gamma(Z' \to add\ dim)/\Gamma_{inv}$ (here $\Gamma_{inv} = \Gamma(Z' \to add\ dim) + \Gamma_i(Z' \to \nu_i\overline{\nu}_i)$) calculated in E$_6$ and LRSM models, respectively, are shown for Z' masses of 1.5 and 3.5 TeV. One can see that the significant part of the (R,k) parameter space satisfies the condition $R \gtrsim 0.3$ even with big uncertainties in the g_L^f coupling, thus making the process $Z' \to add\ dim$ feasible for observation at the LHC.

In summary, we have demonstrated that measurements of the $Z' \to inv$ decay suggest an interesting additional direction to probe extra dimensional physics at the CERN LHC. Although the results presented are model-dependent, we believe that they strengthen current motivations and justify efforts for more sensitive search for the $Z' \to inv$ decay and accurate measurements of its properties in LHC experiments. Detail simulations work, which is beyond the scope of this paper, is in progress [26].

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